Quantifying phosphorus levels in soils, plants, surface water, and shallow groundwater associated with bahiagrass-based pastures

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Abstract

Background, aim, and scope Recent assessments of water quality status have identified eutrophication as one of the major causes of water quality ‘impairment’ not only in the USA but also around the world. In most cases, eutrophication has accelerated by increased inputs of phosphorus due to intensification of crop and animal production systems since the early 1990s. Despite substantial measurements using both laboratory and field techniques, little is known about the spatial and temporal variability of phosphorus dynamics across landscapes, especially in agricultural landscapes with cow-calf operations. Critical to determining environmental balance and accountability is an understanding of phosphorus excreted by animals, phosphorus removal by plants, acceptable losses of phosphorus within the manure management and crop production systems into soil and waters, and export of phosphorus off-farm. Further research effort on optimizing forage-based cow-calf operations to improve pasture sustainability and protect water quality is therefore warranted. We hypothesized that properly managed cow-calf operations in subtropical agroecosystem would not be major contributors to excess loads of phosphorus in surface and ground water. To verify our hypothesis, we examined the comparative concentrations of total phosphorus among soils, forage, surface water, and groundwater beneath bahiagrass-based pastures with cow-calf operations in central Florida, USA.

Materials and methods Soil samples were collected at 0–20; 20–40, 40–60, and 60–100 cm across the landscape (top slope, middle slope, and bottom slope) of 8 ha pasture in the fall and spring of 2004 to 2006. Forage availability and phosphorus uptake of bahiagrass were also measured from the top slope, middle slope, and bottom slope. Bi-weekly (2004–2006) groundwater and surface water samples were taken from wells located at top slope, middle slope, and bottom slope, and from the runoff/seepage area. Concentrations of phosphorus in soils, forage, surface water, and shallow groundwater beneath a bahiagrass-based pasture and forage availability at four different landscape positions and soil depth (for soil samples only) in 2004, 2005, and 2006 were analyzed statistically following a two-way analysis of variance using the SAS PROC general linear models model. Where the F-test indicated a significant ($p \leq 0.05$) effect, means were separated following the method of Duncan multiple range test using the appropriate error mean squares.

Results and discussion Concentrations of soil total phosphorus and degree of phosphorus saturation varied significantly ($p \leq 0.001$) with landscape position and sampling depth, but there was no interaction effect of landscape position and sampling depth. Overall, there was slight buildup of soil total phosphorus. There was no movement of total phosphorus into the soil pedon since average degree of phosphorus saturation in the upper 20 cm was 21% while degree of phosphorus saturation at 60–100 cm was about...
3%. Our livestock operations contributed negligible concentrations of phosphorus to groundwater (0.67 mg L$^{-1}$) and surface water (0.55 mg L$^{-1}$). The greatest forage mass of 6,842 kg ha$^{-1}$ and the greatest phosphorus uptake of 20.4 kg Pha$^{-1}$ were observed at the top slope in 2005. Both forage availability and phosphorus uptake of bahiagrass at the bottom slope were consistently the lowest when averaged across landscape position and years. These results can be attributed to the grazing patterns as animals tend to graze more and leave more excretions at the bottom slope. This behavior may lead to an increase in the concentration of soil phosphorus. Effective use and cycling of phosphorus is critical for pasture productivity and environmental stability. Phosphorus cycling in pastures is complex and interrelated, and pasture management practices can influence the interactions and transformations occurring within the phosphorus cycle.

Conclusions Our results indicate that current pasture management systems which include cattle rotation in terms of grazing days and current fertilizer application (inorganic+ manures+urine) for bahiagrass pastures in subtropical climates on loamy sand soils offer little potential for negatively impacting the environment. Properly managed livestock operations contribute negligible loads of phosphorus to shallow groundwater and surface water. Overall, there was no buildup of soil total phosphorus in bahiagrass-based pasture. Therefore, results of this study may help to renew the focus on improving inorganic fertilizer efficiency in subtropical beef cattle systems and maintaining a balance of phosphorus removed to phosphorus added to ensure healthy forage growth and minimize phosphorus runoff.

Recommendations and perspectives Research on the pathways and rates of movement of phosphorus deposited in urine and dung through various pools and back to the plants will be the focal point of our future investigations. Further studies are needed to determine whether the environmental and ecological implications of grazing and haying in forage-based pastures are satisfied over the longer term. New knowledge based on the whole-farm approach is desirable to identify pastureland at risk of degradation and to prescribe treatments or management practices needed to protect the natural resources while maintaining an economically and environmentally viable operation.

Keywords Bahiagrass · Cow-calf · Nutrient cycling · Phosphorus · Plant uptake · Shallow groundwater · Surface water · Water quality

1 Background, aim, and scope

Forage-based animal production systems with grazing have been suggested as one of the major sources of non-point source phosphorus pollution that are contributing to the degradation of water quality in lakes, reservoirs, rivers, and ground water aquifers (Bogges et al. 1995; Edwards et al. 2000). Cattle manure contains appreciable amounts of nitrogen and phosphorus (0.6% and 0.2%, respectively), and portions of these components can be transported into receiving waters during severe rainstorms (Khaleel et al. 1980). Work in other regions of the country has shown that when grazing animals become concentrated near water bodies or when they have unrestricted long-term access to streams for watering, sediment and nutrient loading can be high (Thurrow 1991; Brooks et al. 1997). Additionally, there is a heightened likelihood of phosphorus losses from over fertilized pastures through surface water runoff or percolation past the root zone (Gburek and Sharpley 1998; Stout et al. 2000). Reduction of phosphorus transport to receiving water bodies has been the primary focus of several studies because phosphorus has been found to be the limiting nutrient for eutrophication in many aquatic systems (Botcher et al. 1999; Sigua et al. 2000; Sigua and Tweedale 2003). Elsewhere, studies of both large (Asmussen et al. 1975) and small watersheds (Romkens et al. 1973; Hubbard and Sheridan 1983) have been performed to answer questions regarding the net effect of agricultural practices on water quality with time or relative to weather, fertility, or cropping practices.

Understanding the effects of water-table management, phosphorus dynamics, and water quality in pastures is the key to reducing phosphorus in runoff. Sharpley (1997) noted that all soils do not contribute equally to phosphorus export from watersheds or have the same potential to transport phosphorus to runoff. In their studies, Coale and Olear (1996) observed that soil test phosphorus levels did not accurately predict total dissolved phosphorus. Better understanding of soil phosphorus dynamics and other crop nutrient changes resulting from different management systems should allow us to predict potential impact on adjacent surface waters. These issues are critical and of increasing importance among environmentalists, ranchers, and public officials in the state (Sigua et al. 2006). One of the first steps in assessing the phosphorus level on any farm is to consider total phosphorus inputs and outputs. Despite substantial measurements using both laboratory and field techniques, little is known about the spatial and temporal variability of phosphorus dynamics across the entire landscape, especially in agricultural landscapes with cow-calf operations. An interest in resource balances in agricultural science dates back to an early experiment in 1930 using balance sheets to show how farm manure and other sources of phosphorus supply (air, rain, and soil) had satisfied crop needs (Scoones and Toulmin 1999). Subsequently, the approaches to input–output analysis became a major focus of systems ecology beginning in the 1950s, when energy, mineral phosphorus, and other cycles were identified (Odum 1988).
Relatively little information exists regarding possible magnitudes of phosphorus losses from grazed pastures. Whether or not phosphorus losses from grazed pastures are significantly greater than background losses and how these losses are affected by soil, forage management, or stocking density are not well understood (Gary et al. 1983; Edwards et al. 2000; Sigua et al. 2004, 2006). A long-term quantitative assessment of soil chemical properties may serve as an indicator of a soil’s capacity for sustainable production of crops and animals in an economically sound, socially acceptable, and environmentally friendly manner (Lemunyon and Gilbert 1993; Sharpley et al. 1996). Critical to determining environmental balance and accountability is an understanding of phosphorus from inorganic fertilizers, phosphorus excreted, phosphorus removal by plants, and acceptable losses of soil phosphorus within the manure management and crop production systems and export of phosphorus off-farm. Further research effort on optimizing forage-based cow-calf operations to improve pasture sustainability and water quality protection therefore is warranted. We hypothesized that properly managed cow-calf operations would not be major contributors to excess loads of phosphorus in surface and ground water in subtropical pastures on loamy soils. To verify our hypothesis, we examined the comparative concentrations of total phosphorus among soils, forage, surface water, and groundwater beneath bahiagrass-based pastures with cow-calf operations.

2 Materials and methods

2.1 Site description

This study (2004–2006) was conducted at the Land Use Unit (28°37′22.8″–28°37′38.2″N; 82°20′07.7″–82°20′31.1″W) of the Subtropical Agricultural Research Station located 7 miles north of Brooksville, FL, USA. The research station has three major pasture units with a combined total area of about 1,558 with 1,295 ha in permanent pastures. Cattle used for nutritional, reproductive, and genetic research on the station include about 500 heads of breeding females with a total inventory of about 1,000 head of cows, calves, and bulls. Cattle production at the station is forage-based with bahiagrass as the predominant forage species (approximately 1,000 ha). Most of the bahiagrass pastures have been established for over 30 years. The soils at the study site are described as loamy, siliceous, hyperthermic family of the Grossarenic Paleudults (Hyde et al. 1977), slopes up to 12% are consistently north facing. Forage production potential of the soils in the station is generally low to medium; the main limitation being soil water availability. The study area is well drained with average soil permeability ranging from 0.004 to 0.014 cm sec⁻¹.

The highest average temperature occurs during August, although highs in the mid-30°C range occur regularly from May through September. The lowest average temperature of 14°C occurs during January, but frosts are frequent during the winter months. The 30-year average annual precipitation at the study site was about 1,262 mm with approximately half of this amount occurring during mid-June through mid-September. The highest monthly total rainfall in 2004 was in September (540 mm). The highest precipitation for 2005 and 2006 were during the months of June (280 mm) and July (275 mm), respectively.

2.2 Pasture management: fertilization and grazing days’ intervals

At the beginning of 1990s, bahiagrass pastures were fertilized annually in the early spring (March) with 77 kg N, 10 kg P, and 37 kg K ha⁻¹ based on the revised fertilizer recommendation suggested by Chambliss (1999). Historically, grazing cattle were rotated among pastures to allow rest periods of 2–4 weeks based on herbage mass. The timing of movement for rotationally grazed was determined by the herd manager’s perception of herbage mass based on plant height and not based on pasture measurement (Williams and Hammond 1999). Starting in 2000, cattle were rotated twice weekly (3- or 4-day grazing period). We anticipated 24 days of rest between pastures, but herd numbers required more frequent grazing periods. During this study, the average number of 3.17 cow-calf pair ha⁻¹ grazed for about 10 days each month. Table 1 shows the number of days grazed each month (2-year average, 2005–2006), average number of animals per hectare, and estimated total manure excreted, total phosphorus from the manure, and total phosphorus after losses (kg ha⁻¹ month⁻¹; Kellogg et al. 2000).

2.3 Instrumentation and water sample collection

Two adjacent 8-ha pasture fields were instrumented with a pair of shallow wells placed at different landscape positions (Fig. 1). The different landscape position are top slope (10–20% slope, 2 ha), middle slope (5–10% slope, 2 ha), and bottom slope (0–5% slope, 2 ha). The wells were constructed of 5 cm schedule 40 polyvinyl chloride (PVC) pipe and had 15 cm of slotted well screening at the bottom. During installation of wells, sand was placed around the slotted screen, and bentonite clay was used to backfill the soil surface to prevent surface water or runoff from moving down the outside of the PVC pipe and contaminating groundwater samples. A centralized battery-operated peristaltic pump was used to collect water samples. Wells were completely evacuated during the sampling process to ensure that water for the next sampling would be fresh groundwater (Hubbard et al. 1986). Water samples were
collected from the groundwater wells every 2 weeks. However, there were periods when ground water levels were below the bottom level of the wells and samples could not be obtained. In addition to ground water samples, surface water samples were collected in the pasture bottoms or the seep area when present, by taking composite grab samples on the same schedule. The seepage area, which is located at the lower end of bottom slope, is a remnant of a sinkhole formation and became a small-scale lake with varying levels of surface water. The seepage area of about 2 ha in size is where runoff and seepage from higher parts of pasture converge. In addition to ground water samples, surface water samples were collected in the pasture bottoms or the seep area when present, by taking composite grab samples on the same schedule.

The average shallow groundwater depth of top slope, middle slope, and bottom slope wells are shown in Fig. 2. The average shallow groundwater depth at the top slope position generally stayed about 600 cm below the surface in 2004 to 2006 except for short-lived rises in April and August 2004 to about 520 and 210 cm below the surface, respectively. More fluctuations (peaks and valleys) in shallow groundwater were observed from the middle slope position compared with other sites in the landscape (see Fig. 2). The fluctuations in shallow groundwater at the bottom slope position were characterized by significant rise and fall between the months of July and December in 2004 and in 2005, respectively. The highest groundwater rise in the bottom slope well occurred in August–September period in 2004, which corresponded to the time that two hurricanes passed over the area.

### 2.4 Water sample handling and analyses

Water samples were transported to the laboratory following collection and refrigerated at 4°C. Water samples were analyzed for total phosphorus using a Flow Injector Phosphorus Analyzer according to standard methods (APHA 1989).

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**Table 1** Monthly grazing activity and estimates of phosphorus contributions from cattle excreta (manure)

<table>
<thead>
<tr>
<th>Months</th>
<th>Average days grazed per pasture</th>
<th>Average number of animals per ha</th>
<th>Animal unit per month(^a)</th>
<th>Total manure excreted(^b)</th>
<th>Total manure phosphorus excreted(^c)</th>
<th>Total phosphorus after losses(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>13.8</td>
<td>2.6</td>
<td>1.0</td>
<td>913</td>
<td>1.73</td>
<td>1.47</td>
</tr>
<tr>
<td>February</td>
<td>9.4</td>
<td>2.5</td>
<td>0.8</td>
<td>669</td>
<td>1.27</td>
<td>1.08</td>
</tr>
<tr>
<td>March</td>
<td>13.5</td>
<td>2.1</td>
<td>0.9</td>
<td>753</td>
<td>1.43</td>
<td>1.22</td>
</tr>
<tr>
<td>April</td>
<td>12.0</td>
<td>2.0</td>
<td>0.7</td>
<td>619</td>
<td>1.18</td>
<td>1.00</td>
</tr>
<tr>
<td>May</td>
<td>12.7</td>
<td>2.1</td>
<td>0.7</td>
<td>654</td>
<td>1.24</td>
<td>1.05</td>
</tr>
<tr>
<td>June</td>
<td>12.0</td>
<td>2.4</td>
<td>0.9</td>
<td>748</td>
<td>1.42</td>
<td>1.21</td>
</tr>
<tr>
<td>July</td>
<td>6.9</td>
<td>3.3</td>
<td>0.7</td>
<td>628</td>
<td>1.19</td>
<td>1.01</td>
</tr>
<tr>
<td>August</td>
<td>9.1</td>
<td>3.6</td>
<td>0.8</td>
<td>734</td>
<td>1.39</td>
<td>1.18</td>
</tr>
<tr>
<td>September</td>
<td>8.2</td>
<td>4.8</td>
<td>1.1</td>
<td>947</td>
<td>1.80</td>
<td>1.53</td>
</tr>
<tr>
<td>October</td>
<td>6.7</td>
<td>5.3</td>
<td>1.1</td>
<td>976</td>
<td>1.85</td>
<td>1.57</td>
</tr>
<tr>
<td>November</td>
<td>6.6</td>
<td>3.6</td>
<td>0.8</td>
<td>705</td>
<td>1.34</td>
<td>1.14</td>
</tr>
<tr>
<td>December</td>
<td>9.4</td>
<td>3.7</td>
<td>1.2</td>
<td>1,037</td>
<td>1.97</td>
<td>1.67</td>
</tr>
<tr>
<td>Total</td>
<td>–</td>
<td>–</td>
<td>10.8</td>
<td>9,347</td>
<td>17.81</td>
<td>15.14</td>
</tr>
</tbody>
</table>

\(^a\) Animal units per month (450 kg cow/calf unit)

\(^b\) Total manure excreted (kg as excreted)=(number of animal units per month×total annual animal manure excretion/12). Total manure excretion (as excreted) per animal per year=10.4 metric tons (Kellogg et al. 2000)

\(^c\) Total phosphorus excreted=total manure excreted×percent total phosphorus in manure (0.19%; Kellogg et al. 2000)

\(^d\) Total phosphorus after losses=based on losses of about 15% (during and after animal excretion)
2.5 Soil sampling and soil analyses

Soil core samples \((n = 16)\) were collected in the spring of 2004 and 2006 from four landscape positions (top slope, middle slope, bottom slope, and seep area) within the pastures. Locations of sampling sites were permanently marked by using a handheld GPS Unit (Garmin GPS 12 CX, Garmin International, Inc., Olathe, KS, USA) for subsequent soil sampling (see Fig. 1). Soil core samples were collected from the 0 to 20, 20 to 40, 40 to 60, and 60 to 100-cm depths from each landscape position using a hydraulic sinker drill (Concord Environmental Equipment, Hawley, MN, USA). Soil samples were air-dried and passed through a 2-mm mesh sieve prior to chemical extraction of soil total phosphorus. Soil total phosphorus was extracted with double acid \((0.025N H_2SO_4 + 0.05N HCl)\) as described by Mehlich (1953) and analyzed using an inductively coupled spectrophotometer. Additional soil samples \((n = 9)\) were collected from three landscape positions (top slope, middle slope, and bottom slope) at two depths (0–20 and 20–40 cm) for total phosphorus analysis. The degree of soil saturation with phosphorus as described in Eq. 1 was computed using the phosphorus, iron, and aluminum contents of the soil (Hooda et al. 2000).

\[
\text{DPS} \% = \left( \frac{[\text{Phosphorus}] \times 100}{[\text{Iron} + \text{Aluminum}]} \right)
\]  

2.6 Plant sampling and phosphorus analysis

Forage availability \((\text{kg ha}^{-1})\) measurements were taken in the early summer and fall of 2004 \((n = 8)\), 2005 \((n = 8)\), and 2006 \((n = 8)\) from four sub-plots around and/or near each groundwater well following the double-ring method of Williams and Hammond (1999). Forage samples were oven-dried at 60°C for 24 h at the US Department of Agriculture, Agricultural Research Service Laboratory in Brooksville, FL, USA, and ground to pass through a 1-mm mesh screen in a Wiley mill and were analyzed for total phosphorus at the University of Florida Analytical Research Laboratory in Gainesville, FL, USA.

2.7 Data reduction and statistical analysis

Concentrations of phosphorus in soils, forage, surface water, and shallow groundwater beneath a bahiagrass-based pasture and forage availability at four different landscape positions and soil depth (for soil samples only) in 2004, 2005, and 2006 were analyzed statistically following a two-way analysis of variance using the SAS PROC general linear models model (SAS Institute 2000). Where the F-test indicated a significant \((p \leq 0.05)\) effect, means were separated following the method of Duncan multiple range test using appropriate error mean squares (SAS Institute 2000). The data were sorted by landscape position when there were differences in the concentration of total phosphorus among surface water, groundwater, soils, and/or forage uptake of phosphorus. Separation of the data by year was done to determine if total phosphorus concentrations were increasing with time (SAS Institute 2000).

3 Results

3.1 Concentration of total phosphorus in surface water and shallow groundwater

The concentration of total phosphorus in surface water was comparable to the levels of total phosphorus in shallow groundwater (Table 2). Levels of total phosphorus varied
widely with landscape position (Fig. 3). Water samples from wells located at top slope (1.8±0.6 mg L\(^{-1}\)) had the greatest concentration of total phosphorus. The average total phosphorus in well water samples from middle slope (0.6±0.3 mg L\(^{-1}\)) and bottom slope (0.5±0.2 mg L\(^{-1}\)) were comparable to the average concentration of total phosphorus (0.5±0.1 mg L\(^{-1}\)) in water samples from the seep area (see Fig. 3). The mean total phosphorus in the wells at the top slope was significantly greater than that found at the middle slope, bottom slope, or in water samples from the seep area (see Fig. 3).

Annual average concentrations of total phosphorus in shallow groundwater and surface water in pastures associated with beef cattle operations varied significantly \((p \leq 0.001)\) with time (see Table 2). The greatest annual average concentration of total phosphorus in shallow groundwater \((1.29 \pm 0.53 \text{ mg L}^{-1})\) was in 2005, while the highest levels of total phosphorus in surface water of \(1.63 \pm 0.27 \text{ mg L}^{-1}\) was in 2004 (see Table 2). Averaged across year, concentrations of total phosphorus in shallow groundwater ranged from 0.001 to 12.79 mg L\(^{-1}\), while concentrations of total phosphorus in surface water ranged from 0.03 to 3.89 mg L\(^{-1}\) (Table 3). Other summary statistics for the levels of total phosphorus in shallow groundwater and surface water are shown in Table 3.

### Table 2 Average (±std. error of mean) concentration of total phosphorus in groundwater, surface water, soils, and bahiagrass in pasture associated with beef cattle operations

<table>
<thead>
<tr>
<th>Year</th>
<th>Shallow groundwater (mg L(^{-1}))</th>
<th>Surface water (mg L(^{-1}))</th>
<th>Soils (mg kg(^{-1}))</th>
<th>Bahiagrass (mg kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>0.28 ± 0.14ab</td>
<td>1.63 ± 0.27a</td>
<td>14.52 ± 1.0a</td>
<td>2,513.33 ± 111.34a</td>
</tr>
<tr>
<td>2005</td>
<td>1.29 ± 0.53a</td>
<td>0.35 ± 0.89b</td>
<td>6.61 ± 0.33b</td>
<td>2,790.33 ± 88.42a</td>
</tr>
<tr>
<td>2006</td>
<td>0.03 ± 0.01ab</td>
<td>0.33 ± 0.08b</td>
<td>6.18 ± 0.61b</td>
<td>2,597.67 ± 98.75a</td>
</tr>
<tr>
<td>Mean</td>
<td>0.67</td>
<td>0.55</td>
<td>9.10</td>
<td>2,633.78</td>
</tr>
<tr>
<td>LSD(_{(0.05)})</td>
<td>1.17</td>
<td>0.46</td>
<td>2.31</td>
<td>301.32</td>
</tr>
</tbody>
</table>

Means in columns within each subheading followed by common letter(s) are not significantly different from each other at \(p \leq 0.05\)

Concentrations of total phosphorus in soils varied significantly \((p \leq 0.001)\) with landscape position and sampling depth, but there was no interaction effect of landscape position and sampling depth (Table 4). Soil samples from the seep area had the lowest concentration of total phosphorus when compared with other landscape positions. Soils from the middle slope \((9.2 \pm 1.8 \text{ mg kg}^{-1})\) had the greatest concentration of total phosphorus followed by top slope \((5.9 \pm 1.8 \text{ mg kg}^{-1})\) and bottom slope \((5.7 \pm 1.5 \text{ mg kg}^{-1})\). Averaged across years, total phosphorus in the soil was about 9.1 mg kg\(^{-1}\) (see Table 2).

Degree of phosphorus saturation in the soils varied significantly \((p \leq 0.001)\) with landscape position and sampling

![Fig. 3](image-url)
depth but was not affected significantly by the interaction of landscape position and sampling depth (see Table 4). The middle slope position (19.9 ± 4.9%) had the highest degree of phosphorus saturation followed by top slope, bottom slope, and seep area. Soils collected at sampling depth of 0–20 cm (20.9 ± 6.1%) had significantly higher degree of phosphorus saturation than soils collected between 20 and 100 cm.

There was a significant ($p \leq 0.05$) decrease in the average concentrations of total phosphorus with increasing sampling depth (see Table 4). The upper two depths (0–20 and 20–40 cm) had the highest concentrations, while the lowest amount of total phosphorus was found in the lowest sampling depth of 60–100 cm (see Table 4). These results suggest that there had been little movement of total phosphorus into the soil pedon since average degree of phosphorus saturation in the upper 20 cm was 21% while degree of phosphorus saturation at lower soil depth (60–100 cm) was about 3%.

3.3 Herbage mass and total phosphorus uptake

There was a significant interaction effect of landscape position and year on the average herbage mass and phosphorus uptake of bahiagrass. The greatest herbage mass (averaged across year) of 3,575 ± 1,223 kg ha$^{-1}$ and the highest phosphorus uptake 10.4 ± 0.6 kg ha$^{-1}$ of bahiagrass were from the top slope position. There was a significant ($p \leq 0.05$) decrease in the average herbage mass and phosphorus uptake with decreasing slope (Table 5). Between the top slope and the bottom slope, herbage mass declined from of 3,575 ± 1,223 to 1,212 ± 9.7 kg ha$^{-1}$, while phosphorus uptake was reduced by approximately 70% (10.4 to 3.2 kg ha$^{-1}$). Both herbage mass and phosphorus uptake at the bottom slope were consistently the lowest when averaged across landscape positions and years, which can be attributed to the grazing activities of the cattle.

Herbage mass and phosphorus uptake (averaged across landscape position) differed among years; the highest average herbage mass and phosphorus uptake were in 2005 of 4,210 kg ha$^{-1}$ forage and 12 kg ha$^{-1}$ of phosphorus (see Table 5). Annual herbage mass of bahiagrass declined by about 46% between 2005 (4,210 kg ha$^{-1}$) and 2006 (2,253 kg ha$^{-1}$). Phosphorus uptake also showed a significant reduction of about 50% between 2005 (12 kg ha$^{-1}$) and 2006 (6 kg ha$^{-1}$).

3.4 Input–output estimates of phosphorus

Livestock grazing plays an important role in soil-phosphorus dynamics as it affects quantity of forage production, forage phosphorus composition, and phosphorus cycling because of the return of phosphorus through animal excretion. Nutrients enter the pasture system from a number of sources: fertilizers, crop residues, atmospheric, and from grazing animals. Nutrients in excreta/urine can be lost via erosion, runoff, animal ingestion (Boddey et al. 2004; Yan et al. 2007), leaching to groundwater, (Tamminga 2006), and haying (Fig. 4).

Table 4 Average concentration (±std. error of mean) and $F$-values of total phosphorus and degree of phosphorus saturation in soils at various landscape positions and soil depths

<table>
<thead>
<tr>
<th>Soil parameters</th>
<th>Total phosphorus (mg kg$^{-1}$)</th>
<th>Degree of phosphorus saturation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landscape position</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top slope</td>
<td>5.91 ± 1.77b</td>
<td>14.79 ± 4.57a</td>
</tr>
<tr>
<td>Middle slope</td>
<td>9.19 ± 1.77a</td>
<td>19.92 ± 4.97a</td>
</tr>
<tr>
<td>Bottom slope</td>
<td>5.67 ± 1.53b</td>
<td>7.86 ± 2.14b</td>
</tr>
<tr>
<td>Seep area</td>
<td>0.38 ± 0.13c</td>
<td>1.25 ± 0.73c</td>
</tr>
<tr>
<td>LSD$_{(0.05)}$</td>
<td>2.62</td>
<td>6.35</td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–20</td>
<td>7.05 ± 1.86a</td>
<td>20.93 ± 6.11a</td>
</tr>
<tr>
<td>20–40</td>
<td>9.05 ± 2.18a</td>
<td>13.77 ± 3.22b</td>
</tr>
<tr>
<td>40–60</td>
<td>3.24 ± 0.94b</td>
<td>5.64 ± 1.67c</td>
</tr>
<tr>
<td>60–100</td>
<td>1.81 ± 0.62b</td>
<td>3.47 ± 1.06c</td>
</tr>
<tr>
<td>LSD$_{(0.05)}$</td>
<td>2.62</td>
<td>6.35</td>
</tr>
</tbody>
</table>

Means in columns within each subheading followed by common letter (s) are not significantly different from each other at $p \leq 0.05$

$^*$Significant at $p \leq 0.001$

$ns$ Not significant
The estimation of major phosphorus input components in this system per year were summarized as follows: fertilizer application (10 kg P ha\(^{-1}\) year\(^{-1}\) or 32% of total input; Sigua et al. 2008), animal excreta (18 kg N ha\(^{-1}\) year\(^{-1}\) or 57% of total input; see Table 1), and atmospheric deposition (3.7 kg N ha\(^{-1}\) year\(^{-1}\) or 11% of total input; Poor et al. 2001). The major output component was uptake by herbage (20 kg N ha\(^{-1}\) year\(^{-1}\); Sigua et al. 2008). Our input–output estimations yielded an annual net soil gain of 2.6 kg P ha\(^{-1}\) year\(^{-1}\). The average amount of total phosphorus measured in the shallow groundwater was about 2.3% of the total output, while the amount of total phosphorus measured from runoff represented 1.9% of the total output component (Sigua et al. 2008).

### 4 Discussion

When livestock tend to graze some pastured areas more than others, plant communities can degrade, and soil physical and chemical attributes can change with time. Interestingly, highest concentrations of soil total phosphorus in the soil in our study were not found at the bottom slope position but at the middle slope and top slope positions, which were closest to the mineral feeders and water troughs. White et al. (2001) claimed that there was a correlation between time spent in a particular area and the number of excretions received, and this behavior could lead to an increase in the concentration of soil phosphorus close to shade and water. Preliminary work of Sigua and Coleman (2007) demonstrated that concentrations of soil total phosphorus varied significantly among the different congregation sites (water, mineral, and shade) on bahiagrass-based pastures in Florida.

Overall, there was a very low net gain of soil phosphorus at any of the landscape position, but there had been no movement of total phosphorus into the soil pedon since the average degree of phosphorus saturation in the upper 20 cm was 21% while the average degree of phosphorus saturation at 60–100 cm was about 3%. Several studies (Heckrath et al. 1995; Hooda et al. 2000) have found that degree of phosphorus saturation in soils needs to exceed 45% to 60% before dissolved reactive phosphorus becomes an environmental problem. Our results do not even approach this level of degree of phosphorus saturation, suggesting that phosphorus buildup and release is not a predicament. Our input–output estimations yielded a low net gain of soil phosphorus (2.6 kg P ha\(^{-1}\)). It should be noted that for a farm to be sustainable, its phosphorus budget should balance, at least after soil reserves are brought up to desired levels for sustainable production. If there is a net loss of phosphorus (as observed in our study), the farm’s soils will eventually become depleted, and if there is an excess, the likelihood of pollution is greater (Van Horn et al. 1996). Effective use and cycling of phosphorus is critical for pasture productivity and environmental stability. Phosphorus cycling in pastures is complex and interrelated, and pasture management

**Table 5** Average herbage mass and phosphorus uptake of bahiagrass as affected by landscape position by year interactions

<table>
<thead>
<tr>
<th>Landscape position</th>
<th>Year</th>
<th>Herbage mass (kg ha(^{-1}))</th>
<th>Phosphorus uptake (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top slope</td>
<td>2004</td>
<td>777.5 ± 37.2d</td>
<td>1.9 ± 0.1c</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>6,842.5 ± 1,037.0a</td>
<td>20.4 ± 0.1a</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>3,104.0 ± 443.3bc</td>
<td>8.8 ± 1.5bc</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>3,575.0 ± 505.8</td>
<td>10.4 ± 0.6</td>
</tr>
<tr>
<td>Middle slope</td>
<td>2004</td>
<td>680.0 ± 3.5d</td>
<td>1.6 ± 0.1c</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>4,216.5 ± 182.2b</td>
<td>11.3 ± 0.9b</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>2,214.5 ± 71.3bcd</td>
<td>5.8 ± 0.4bc</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>2,370.3 ± 85.7</td>
<td>6.2 ± 0.5</td>
</tr>
<tr>
<td>Bottom slope</td>
<td>2004</td>
<td>625.5 ± 8.4d</td>
<td>1.7 ± 0.1c</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>1,571.0 ± 10.9 cd</td>
<td>4.4 ± 0.04bc</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>1,440.5 ± 9.5 cd</td>
<td>3.4 ± 0.1bc</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>1,212.3 ± 9.6</td>
<td>3.2 ± 0.08</td>
</tr>
</tbody>
</table>

Means within each columns followed by common letter(s) are not significantly different from each other at \(p \leq 0.05\)
practices influence the interactions and transformations occurring within the phosphorus cycle (see Fig. 4).

On average, we did not find the concentrations of total phosphorus in surface water to be distinctly different \((p \geq 0.05)\) from the amount of total phosphorus in shallow groundwater, although the concentration of total phosphorus in top slope wells was significantly greater than that of water samples from the middle slope wells, bottom slope wells, and from the seepage area. Non-uniform grazing distribution by livestock on landscapes can be caused by many variables such as water location (Holechek 1988; Ganskopp 2001), minerals (Martin and Ward 1973), herbage mass (Senft et al. 1983), and ruggedness (slope) of the terrain, which exist at a variety of scales (Smith 1988). In our pastures, slope position was confounded with mineral, water source, and to some degree shade, which were located near the top slope and bottom slope positions. This would have exacerbated the non-uniform grazing distribution attributed to slope position. The estimated amount of total phosphorus that was gained by the soil \((2.6 \text{ kg P ha}^{-1})\) suggests that the current recommendations for phosphorus might be somewhat low to adequately maintain and sustain growth of bahiagrass. Periodic applications of additional phosphorus may be necessary to sustain agronomic needs and to offset the export of phosphorus due to animal production. Grazing activities of the cattle had affected herbage mass. The average herbage mass in our study was highest at the top slope position \((3,574 \text{ kg ha}^{-1})\) > middle slope \((2,370 \text{ kg ha}^{-1})\) > bottom slope \((1,212 \text{ kg ha}^{-1})\). We observed consistently that our animals (cow-calf) tended to graze more at the bottom slope than in middle slope or top slope of our pastures. Observations of animal movement with visual inspection based on actual positions of the test animals within the pasture at 8:30 a.m. and at 2:00 p.m. on a daily basis disclosed that 40% to 50% of the time cows in herds were grazing at the bottom slope of the pasture (unpublished data). In our pastures, slope position was confounded with mineral, water source, and to some degree shade, which were located near the top slope and bottom slope position. Abiotic factors such slope positions and distances to water are the primary determinants of grazing distribution at our study site. This effect on herbage mass accounts for most of the differences found in total phosphorus held by forage on a per hectare basis. Between the top slope and the bottom slope positions, total phosphorus in the forage expressed as a unit area declined by about 70% \((10.4 \text{ to } 3.2 \text{ kg ha}^{-1})\), respectively.

5 Conclusions

Our results indicate that current pasture management including cattle rotation in terms of grazing days and current fertilizer (inorganic+manures+urine) application rates for bahiagrass pastures offer little potential for negatively impacting the environment. Properly managed livestock operations contribute negligible loads of total phosphorus to shallow groundwater and surface water. Overall, there was no buildup of soil total phosphorus in bahiagrass-based pasture. Therefore, results of this study may help to renew the focus on improving fertilizer efficiency in subtropical beef cattle systems and maintaining a balance of phosphorus removed to phosphorus added to ensure healthy forage growth and minimize phosphorus runoff.

6 Recommendations and perspectives

Additional research on the pathways and rates of movement of phosphorus deposited in cattle urine and dung through various pools and back to forage plants is needed. Further studies should be needed to determine the environmental and ecological implications of long-term grazing and haying management systems for forage-based pastures. New knowledge based on the whole-farm approach is desirable to identify pastureland at risk of degradation and to prescribe treatments or management practices needed to protect natural resources while maintaining an economically and environmentally viable animal production systems.

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